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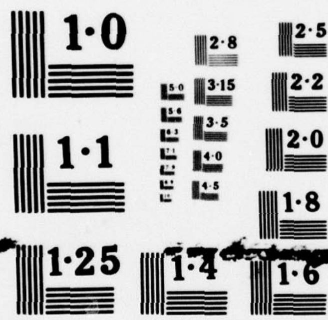

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Two advanced gear materials (Timken CBS 1000M and Carpenter Cartech EX00014) and an AMS 6260 gear material were evaluated in combination with three lubricants (unformulated basestock ester, a qualified MIL-L-23699B, and an XAS-2354 lubricant) to determine their gear scuffing/scoring capacities. The results show that (1) the CBS 1000M steel is superior to AMS 6260 with the lubricants evaluated; (2) the EX00014 steel is superior to the AMS 6260 with the formulated lubricants; and (3) the XAS-2354A lubricant showed significant load carrying capacity improvements for all three gear steels.

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NAVAL AIR PROPULSION CENTER

TRENTON, NEW JERSEY 08628

PROPULSION TECHNOLOGY AND PROJECT ENGINEERING DEPARTMENT

NAPC-PE-10 AUGUST 1978

ADVANCED GEAR STEELS AND LUBRICANTS FOR IMPROVED GEAR TOOTH SCUFFING/SCORING RESISTANCE FOR AIRCRAFT APPLICATIONS

PHASE REPORT

Prepared by: Daniel Popgoshev
D. POPGOSHEV

Approved by: A L Lockwood
A. L. LOCKWOOD

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LIST OF SYMBOLS

SYMBOLS	DEFINITION
AISI	American Iron and Steel Institute
AMS	Aerospace Material Specification
ANOVA	Analysis of Variance
ASTM	American Society for Testing and Materials

CONVERSION FACTORS: SI to U.S. CUSTOMARY UNITS

TO CONVERT FROM	TO	MULTIPLY BY
degree Kelvin (^{O}K)	degree Fahrenheit (^{O}F)	$t_F = t_K(1.8) - 459.67$
metre (m)	inch (in)	39.370079
newtons per metre (n/m)	pounds-force per inch (PPI)	0.005710
Pascals (Pa)	pounds-force per inch^2 (Psi)	1.450377×10^4

INTRODUCTION

The current trends and future requirements in gearbox and transmission systems for aircraft are towards decreased specific weights. Consequently, advanced power drive systems will require gear steels and lubricants with the capabilities of operating reliably, (i.e. without scuffing or scoring), at increased loads, temperatures, and speeds. Improvements in gear materials, lubricants/additives, and their interactions provide a means of achieving increases in gear score load carrying capacity to offset the detrimental effects of the severe operating conditions in advanced systems. This program was therefore initiated to investigate new lubricants. The aim of the program is to obtain significantly improved gear scuff/score load carrying capacities over the conventionally used Aerospace Material Specification (AMS) 6260,(American Iron and Steel Institute (AISI) 9310)gear material. The candidate gear materials for evaluation include Carpenter Steel Corporation Cartech EX00014 and Cartech EX00053, Timken Steel Corporation CBS 600 and CBS 1000M and the Teledyne Corporation VASCO X-2. To date the CBS 1000M and the Cartech EX00014 have been evaluated with AMS 6260 as a baseline and in combination with three lubricants, namely: a basestock used in formulating MIL-L-23699B lubricants, a qualified MIL-L-23699B lubricant, reference 1, and a lubricant qualified for the experimental specification XAS-2354, reference 2.

The vehicle used for evaluation is the Ryder Gear Machine which has been used extensively in evaluating the load carrying capacity of lubricants and to some extent new gear materials.

The purpose of this report is document the work conducted to date in this evaluation program.

This work was authorized by reference 3.

CONCLUSIONS

1. The scuffing/scoring resistance of the Timken CBS 1000M steel is significantly superior to the standard AMS 6260 (AISI 9310) steel and to the Cartech EX00014 steel regardless of the lubricant used.

2. When tested with a basestock lubricant, the Cartech EX00014 steel shows no scuffing/scoring improvement over the standard AMS 6260 steel.

3. The Cartech EX00014 steel/MIL-L-23699B lubricant combination yields a 21 percent scuffing/scoring improvement over an AMS 6260 steel/MIL-L-23699B lubricant combination.

4. The Cartech EX00014 steel/ XAS-2354 lubricant combination yields an eight percent scuffing/scoring improvement over an AMS 6260 steel/XAS-2354 lubricant combination.

5. The XAS-2354 lubricant showed the most significant improvements in the relative scuffing/scoring capacity of the lubricants used. Moreover, the MIL-L-23699B fully formulated lubricant was superior to the basestock lubricant

RECOMMENDATIONS

1. In order to more closely reflect the operational characteristics of advanced transmission systems, the CBS 1000M steel should be further evaluated at elevated oil temperatures.

2. The program should be continued to evaluate other new gear material and lubricant combinations. Specifically, the advanced gear steels Timken CBS 600, Cartech EX00053, and VASCO X2 should be evaluated. The data generated in such an evaluation will give propulsion/drive system designers alternatives for improving performance.

DESCRIPTION

Ryder Test Machine

1. All testing was conducted utilizing the Erdco Engineering Corporation Ryder Gear Machine with an improved high speed/high temperature version of the standard test head known as the Ryder Research Gear Head (also referred to as the WADD Head). A schematic cross-section of this test head is shown in Figure 1. Gear tooth loading on the Ryder Gear Machine is achieved by use of the four square principle in which a torque is locked into two parallel shafts by two interconnected sets of gears. One set of gears is the replaceable test gears while the other set is a helical slave/drive mesh. Load is applied hydraulically through the axial movement of one shaft relative to the other. The relation between tooth load and load oil pressure is therefore a function a helical gear helix angle and shaft displacement. With this type of loading only a fraction of the power being simulated is required to drive the system because it is only necessary to overcome frictional losses.

2. The Ryder Research Gear Machine has been used extensively in the determination of the load carrying capacity of lubricants. The procedures and methods of operating the Ryder Test Machine are standarized through the American Society for Testing and Materials (ASTM) Test Method D-1947 and Method 6512 of Federal Test Method Standard No. 791b (references 4 and 5 respectively).

Test Gears

3. Test Gears for this program were made of the following materials:

a. AMS 6260 (AISI 9310) - Baseline Gears

b. Timken Steel Corporation Alloy CBS 1000M

c. Carpenter Steel Corporation Alloy Cartech EX00014

The AMS 6260 steel is a standard gear material used extensively in helicopter transmissions and engine gearboxes. For this reason it was used as a baseline or control steel against which the other two steels were compared. The CBS 1000M and the EX00014 materials are experimental steels. The analysis and hardness characteristics of these steels as compared to AMS 6260 is presented in Table I. It is important to note that the CBS 1000M retains its hardness at much higher temperatures than do the other two steels. The CBS 1000M, has an excellent potential for use at the elevated temperatures expected of advanced transmission systems.

4. All test gears were manufactured in accordance with the dimensional specifications as provided by the ASTM through Test Method D-1947. Each gear has 28 teeth, 0.0889M (3.5 in.) pitch diameter, eight diametral pitch, and a 22.5 degree pressure angle. A gear set consists of a test (narrow) gear with a nominal 0.00635M (0.25 in.) tooth width and a mating/load gear with a nominal 0.0238M (0.935 in.) tooth width. In addition, the baseline (AMS 6260) gears were made in accordance with the metallurgical specifications required by the ASTM Test Method D-1947.

Lubricants

5. Three different types of synthetic lubricants were used in this evaluation. They consisted of:

a. Hercolube C Basestock Lubricant - this is a standard unformulated single acid (C_5) pentaerythritol ester basestock lubricant made by Hercules Powder Company, commonly used for comparison with the score load carrying capacity of fully formulated lubricants.

b. A Qualified MIL-L-23699B Lubricant - one qualified lubricant was selected based on a survey of the currently available lubricants in the Navy inventory (PVO International STO 21919A). This particular lubricant used was determined to be in plentiful supply and representative of other MIL-L-23699B lubricants.

c. An XAS-2354 Lubricant - this is an advanced high temperature/high gear load lubricant for aircraft propulsion systems developed for the Navy experimental specification XAS-2354. The lubricant used in this program is the Shell Oil Company Aero Shell Turbine Oil 555.

METHOD OF TEST

1. The test methods and procedures used in this program were generally as specified in the ASTM Test Method D-1947-77. Basically this test method consists of a) stabilizing all bulk lubricant temperatures at $355.4^{\circ}K$ ($180^{\circ}F$), b) an operating speed of (10,000 RPM) for the test gears, and c) increments of 68.95 KPa (10 psi) in load oil pressure every ten minutes until a failure occurs (22.5 percent of gear tooth scuff).

The following exceptions to the standard ASTM method were followed:

a. A closed circuit television system is used in the gear rating process rather than a microscope.

b. The material of the experimental test gears was not the standard AMS 6260 steel.

c. A load oil pressure increment of 68.95 Kpa (10 psi) was used rather than the 34.47 KPa (5 psi) specification increment. This is due to the differences in machine constants between the Ryder Research and Ryder Gear Heads. Prior experience at the Naval Air Propulsion Center (NAPC) has shown this change to have no effect on the rating of the load carrying capacity.

2. Each of the three gear materials were evaluated on each of the three lubricants. Four scuffing/scoring determinations were made on each lubricant/steel combination for a total of 36 data points (3 steels x 3 lubricants x 4 determinations). The tests were run in a random manner in order to insure that any extraneous factors were distributed throughout the results and would not bias the data.

3. An Analysis of Variance (ANOVA) was performed on the data in order to determine the effects of gear material, lubricant, and gear material/lubricant interaction on load carrying capacity.

DISCUSSION AND ANALYSIS OF RESULTS

1. The results of the test program are presented in Table II. These data were analyzed statistically by ANOVA techniques so that inferences concerning the effects of lubricants, steels, and lubricant/steel combinations could be made. Details of the ANOVA calculations are presented in Appendix A. All three effects were found to be significant with at least 95 percent certainty. These effects can more clearly be visualized in the graph presented in Figure 2. The main effects of the lubricant and gear material are strong indicating that:

a. CBS 1000M steel is superior to both Cartech EX00014 and AMS 6260 steels.

b. XAS-2354 lubricant is superior to MIL-L-23699B lubricant which in turn is superior to the basestock lubricant.

The best performing combination may therefore be achieved with the use of CBS 1000M steel in combination with the XAS-2354 lubricant. The interaction effect, although statistically significant, is not nearly as strong as the main effects as indicated by the F-ratio's of the ANOVA Table of Appendix A. The interaction effect can be visually identified in Figure 2. Although the Cartech EX00014 steel is no better than the AMS 6260 steel with the basestock lubricant it interacts favorably with the additives of the MIL-L-23699B and XAS-2354

lubricants to give performance superior to the AMS 6260.

2. The data of Figure 2 are presented in a different form in Table III in order to show percentage change in load carrying capacity using the MIL-L-23699B lubricant/AMS 6260 gear steel combination as a baseline. This is of interest since the data indicate improvements that may be reasonably expected over the currently used lubricants (MIL-L-23699B) and gear material (AMS 6260) by the use of advanced lubricants (XAS-2354 and gear material (CBS 1000M). The most notable features in Table III are:

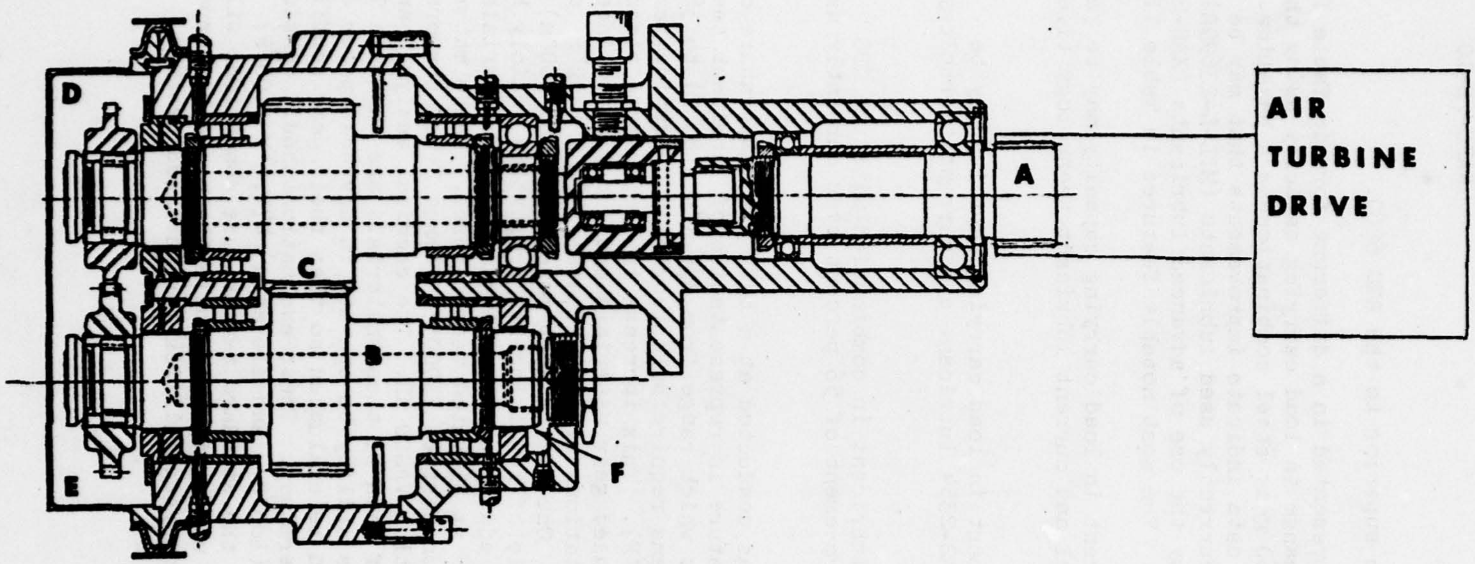
a. An increase of 35 percent in load carrying capacity may be realized with the use of CBS 1000M steel and current lubricant technology (i.e. MIL-L-23699B).

b. An increase of 26 percent in load carrying capacity may be realized with the use of an XAS-2354 lubricant and current technology gear steel (AMS 6260).

c. A change to XAS-2354 lubricant in combination with the CBS 1000M steel results in an improvement of 56 percent over currently used technology.

3. This entire test series was conducted at a bulk oil temperature of 355.4°K (180°F). This temperature is representative of lubricant temperatures in current power drive systems which range from 355.4°K (180°F) to 386.9°K (235°F). Advanced drive systems require bulk lubricant operating temperatures of approximately 477.6°K (400°F). This increase in temperature places extreme demands on currently used gear materials and lubricants since they have maximum temperature limitations of approximately 422°K (300°F) and 477.6°K (400°F) respectively. One of the gear materials (CBS 1000M) evaluated in this test program is capable of retaining its properties (mainly hardness) at elevated temperatures. In addition, other advanced gear materials are capable of sustained operation at elevated temperatures. These materials, are Carpenter Steel Corporation Cartech EX00053, Timken Steel Corporation CBS 600, and Teledyne Corporation VASCO X2. The chemical analysis and maximum service temperature of each of these materials are shown in Table IV. Since these materials have the ability to operate in advanced power drive system environments they should be evaluated so that their gear scuffing/scoring properties may be determined. These evaluations should consist of testing at standard 355.4°K (180°F) and elevated 477.6°K (400°F) temperatures. In this manner the standard temperature conditions will yield comparisons to conventionally used materials while the elevated temperature condition will yield comparisons/capabilities for advanced systems.

FIGURE 1: CROSS SECTION OF THE RYDER RESEARCH GEAR MACHINE TEST HEAD



LEGEND

- **A** Drive Shaft
- **B** Driven (Load) Shaft
- **C** Helical Slave Gears
- **D** Test Gear (Narrow)
- **E** Load Gear (Wide)
- **F** Load Chamber

FIGURE 2: GEAR LOAD CAPACITIES OF COMBINATIONS OF STANDARD AND ADVANCED MATERIALS AND LUBRICANTS

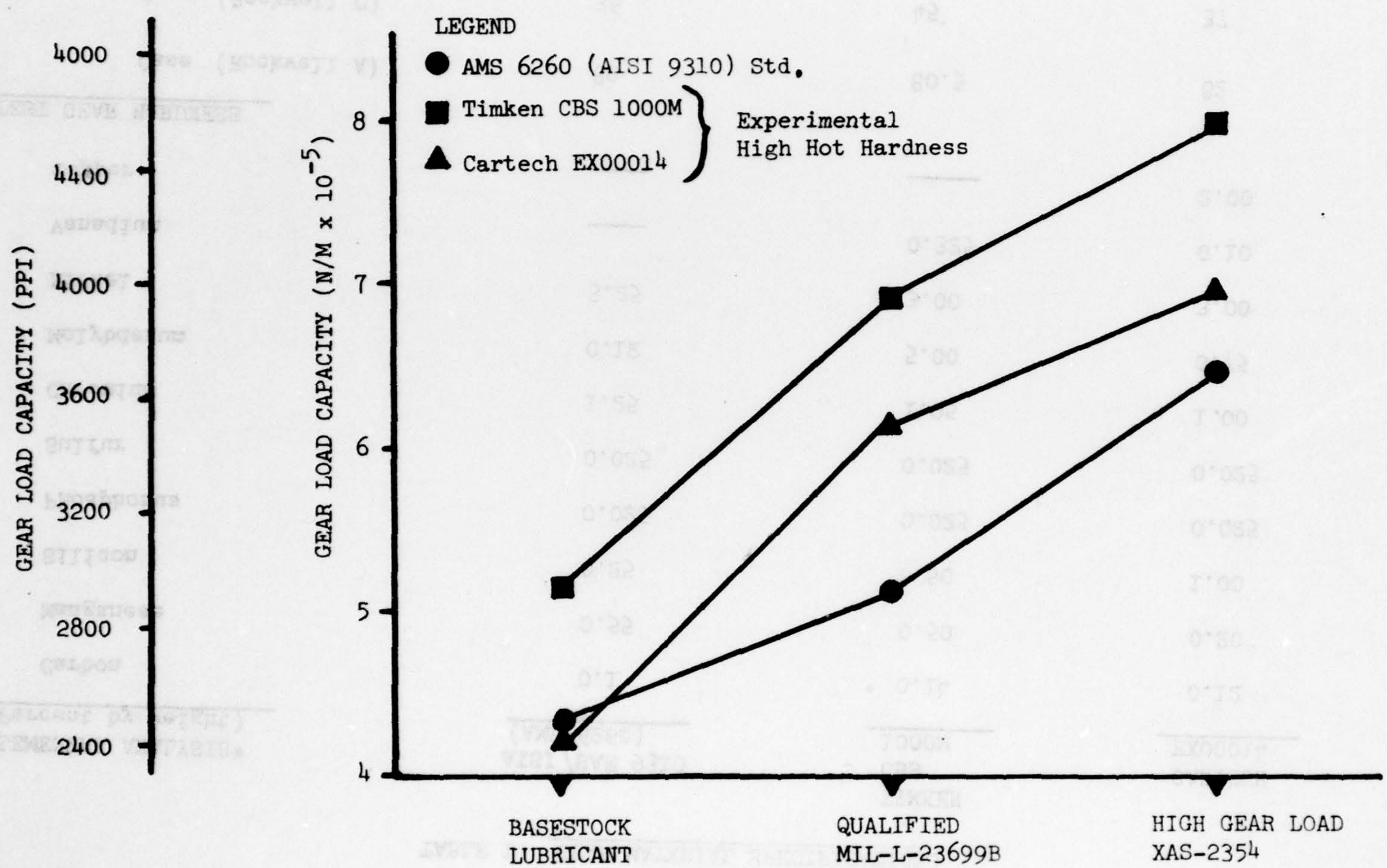


TABLE I: GEAR MATERIAL SPECIFICATIONS

	AISI/SAE 9310 (AMS 6260)	TIMKEN CBS 1000M	CARTECH EX00014
1. ELEMENTAL ANALYSIS* (Percent by weight)			
Carbon	0.1	0.14	0.12
Manganese	0.55	0.50	0.20
Silicon	0.25	0.50	1.00
Phosphorus	0.025	0.025	0.025
Sulfur	0.025	0.025	0.025
Chromium	1.25	1.05	1.00
Molybdenum	0.12	5.00	0.75
Nickel	3.25	3.00	3.00
Vanadium	—	0.325	0.10
Copper	—	—	2.00
2. TEST GEAR HARDNESS			
Case (Rockwell A)	80	80.5	82
Core (Rockwell C)	36	45	37
3. MAX SERVICE TEMP., ^{o}K (^{o}F)	422 (300)	589 (600)	450 (350)

* Balance Iron

TABLE II: RESULTS OF LUBRICANT/MATERIAL EVALUATION ON RYDER GEAR MACHINE

LUBRICANT	MATERIAL: AISI /SAE 9310 (AMS 6260)		TIMKEN CBS 1000M		CARTECH EX00014	
BASESTOCK	399639	(2282)	533086	(3044)	356908	(2038)
	399989	(2284)	544820	(3111)	401215	(2291)
	432563	(2470)	494383	(2823)	413825	(2363)
	394561	(2253)	481774	(2751)	495959	(2832)
AVERAGE	432957	(2472)	513516	(2932)	416977	(2381)
QUALIFIED MIL-L-23699B	482999	(2758)	743238	(4244)	614520	(3509)
	494208	(2822)	677741	(3870)	625553	(3572)
	512421	(2926)	626604	(3578)	610142	(3484)
	548672	(3133)	706286	(4033)	610142	(3484)
AVERAGE	509575	(2910)	688467	(3931)	615089	(3512)
XAS-2354	654274	(3736)	788771	(4504)	725725	(4144)
	647094	(3695)	791223	(4518)	686497	(3920)
	610317	(3485)	776687	(4435)	643766	(3676)
	656025	(3746)	824847	(4710)	715218	(4084)
AVERAGE	641927	(3665)	795382	(4542)	692802	(3956)

NOTE: Results given are load carrying capacity in newtons per metre (pound-force per inch) of gear tooth width.

TABLE III: RELATIVE LUBRICANT/MATERIAL LOAD CAPACITY WITH RESPECT TO A MIL-L-23699B/AMS 6260 COMBINATIONS

	AISI/SAE 9310 (AMS 6260)	TIMKEN CBS 1000M	CARTECH EX00014
HERCOLUBE C BASESTOCK ABSOLUTE CHANGE IN RATING N/M (PPI)	-76618 (-437)	3940 (22)	-92598 (-528)
PERCENT CHANGE	-15	1	-18
MIL-L-23699B ABSOLUTE CHANGE IN RATING N/M (PPI)	BASELINE	178892 (1021)	105514 (602)
PERCENT CHANGE	BASELINE	35	21
XAS-2354 ABSOLUTE CHANGE IN RATING N/M (PPI)	132532 (755)	285806 (1632)	183226 (1046)
PERCENT CHANGE	26	56	36

TABLE IV: ADVANCED GEAR MATERIAL SPECIFICATIONS

1. ELEMENTAL ANALYSIS* (Percent by weight)	CARTECH EX00053	TIMKEN CBS 600	TELEDYNE VASCO X2
Carbon	0.10	0.19	0.14
Manganese	0.35	0.55	0.30
Silicon	1.00	1.10	0.90
Phosphorus	0.010 max.	0.025 max.	0.015 max.
Sulfur	0.010 max.	0.025 max.	0.015 max.
Chromium	1.00	1.40	5.00
Molybdenum	3.25	1.00	1.40
Nickel	2.00	-	-
Vanadium	0.10	-	0.45
Copper	2.00	-	-
Tungsten	—	—	1.35
2. Max. Service Temp., ^{o}K (^{o}F)	589 (600)	505 (450)	589 (600)

*Balance Iron

REFERENCES

1. SPECIFICATION: Lubricating Oil Aircraft Turbine Engine, Synthetic Base" MIL-L-23699B Amd. 2 of 22 November 1971

2. SPECIFICATION: "Lubricating Oil, Aircraft Turbine Engines Synthetic Base, XAS-2354 of 1 November 1969

3. AUTHORIZATION: NAVAIR Airtask 5365360/053F/8W05980000; NAPC Work Unit Assignment 4R6 712

4. TEST METHOD: American Society for Testing and Materials Method D-1947-77

5. TEST METHOD: Federal Test Method Standard 791b Method 6512

APPENDIX A

1. The Analysis of Variance (ANOVA) is a statistical method which is used to determine the influence of control variables on an observation. This technique is described in detail in "Introduction to Statistical Analysis" by Dixon and Massey. Only a general description and the final analysis of the results will be outlined here.

2. A control variable is said to influence the response only if its effect on the response is greater than can be explained by experimental error or random causes. A suitable statistical test, called an F-test, exists for determining with a desired degree of certainty whether or not the variable in question has a real influence on the response.

3. Four basic steps are followed in applying the above method of analysis to the data:

a. Calculate a measure of the variation in the data due to changing the level of the variable in question. (e.g. changing from one material to another) This calculated value is the Mean Square.

b. Calculate a measure of the variation in the data due to random causes or experimental error by considering the variation occuring at each level of the variable. This value is the Within Groups Mean Square.

c. Take the ratio of the Mean Square for each variable to the Within Groups Mean Square. This value is the called the F-ratio.

d. Compare the F-ratio for each variable to a critical F-value selected from a statistical table. If the calculated F-ratio is greater than the critical F-value then the variable in question is said to influence the response.

4. The magnitude of the critical F-value used in testing if a variable has an effect on the response varies according to the number of variables, the number of levels of each variable, and the degree of certainty that is desired in determining the influence of the variable.

5. By following the methods described in "Introduction to Statistical Analysis" an ANOVA table may be generated. Such a table for the data which is presented in Table II of the main body of the report is presented in Table A-1. The heading marked $F_{.05}$ represents the critical value of F. If the calculated F-ratio is greater than this value then there is 95 percent certainty that the variable in question does influence the response. It is sometimes said that the variable has a significant effect at the 5 percent level of significance or that there are five chances in a hundred that the variable does not affect the response.

6. All the variables listed in Table A-1 were tested at the 5 percent level of significance. They were found to be significant at this level i.e. there are real material, lubricant, and interaction (material-lubricant) effects present.

TABLE A1

RESULTS OF ANOVA ON THE TEST DATA

	SUM OF SQUARES N^2/M^2 $(PPI)^2$	DEGREE OF FREEDOM	MEAN SQUARE N^2/M^2 $(PPI)^2$	F-RATIO	CRITICAL $F_{.05}$ VALUE
Row Mean Values (Lubricant)	3.958×10^{11} (12904060)	2	1.979×10^{11} (6452030)	143.59	5.49
Column Mean Values (Material)	1.175×10^{11} (3832411)	2	(5.877×10^{10} (1916206)	42.64	5.49
Interaction	1.745×10^{10} (569109)	4	4.364×10^{9} (142277)	3.16	4.11
Subtotal	5.308×10^{11}	8	6.634×10^{10}		
Within Groups	3.721×10^{10}	27	1.378×10^{9}		
Total	5.680×10^{11} (18518820)	35	1.623×10^{10} (529109)		

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